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RAILWAY LINEHAUL ENERGY INTENSITY: REVIEW OF AAR TRAIN ENERGY MODEL AND VALIDATION DATA AVAILABILITY

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17. Abstract

This report is the second in a series of CIGGT reports on Railway Linehaul Energy Intensity sponsored by Transport Canada. The first report (CIGGT Report #80-15, "Railway Linehaul Energy Intensity: An Analysis Leading to Design of a Train Simulation Software Package, 1980") outlined a research and development program with some emphasis on the attributes of a train simulation computer program. This report presents a review of a train energy computer program being developed by the Association of American Railroads (AAR) and an evaluation of the usefulness of existing data relevant to train resistance. The review of the AAR model led to recommendations of changes to some modules but concluded with the recommendation that, given its modular structure and state of development, the program be adopted as the industry standard and taken as the base starting program for future developments. The review of existing data sources revealed definite limitations and led to an opportunity to participate in some current train resistance field tests with Canadian National Railways. Recommendations for data collection and analysis are made.

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17. Résumé

Ce rapport est le deuxième d'une série publiée par le Canadian Institute of Guided Ground Transport (CIGGT) sur la recherche qu'il a faite pour le compte de Transports Canada en ce qui concerne l'estimation de la dépense d'énergie des trains. Le premier rapport du CIGGT no 80-15 intitulé: Railway Linehaul Energy Intensity: An analysis Leading to design of a Train Simulation Software Package, 1980, esquissait un programme de R&D où il insistait sur les caractéristiques que devrait avoir un programme de simulation informatique de la marche des trains. Le présent rapport décrit le modèle de simulation étudié par l'Association of American Railroads (AAR) des Etats-Unis et évalue la pertinence des données existantes sur la résistance à la marche des trains. Il recommande d'apporter des modifications à certains modules du modèle de l'AAR et propose que, vu sa structure modulaire et l'état de développement où il est arrivé, ce modèle devienne la norme en la matière et constitue le point de départ des modèles ultérieurs. Les lacunes trouvées dans les données existantes montrent l'utilité de collaborer avec le CN à quelques-uns des essais in situ sur la résistance à la marche. Le rapport termine en formulant des recommandations sur la saisie et le dépouillement des données.

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TABLE OF CONTENTS

1. INTRODUCTION 1

2. AAR TRAIN ENERGY MODEL 2

3. DATA AVAILABILITY 4
   3.1 Existing Data 4
   3.2 Imminent Data 10
      3.2.1 Test Proposal in Conjunction with CN Rail's Intermodal Tests 10

Appendix A: REVIEW OF THE AAR TRAIN ENERGY MODEL

LIST OF TABLES

1. Comparison of Significant Independent Variables Affecting Different Train Resistance Components 7

2. Required Level of Effort to Process Data 9

LIST OF FIGURES

1. AAR Train Energy Model program structure 3

2. Conductor's train journal report 5

3. A sample proposed resistance test section 12

1. INTRODUCTION

In 1980, the Canadian Institute of Guided Ground Transport (CIGGT) conducted a study for Transport Canada on the feasibility of developing a computer program capable of accurately estimating railway linehaul energy use on a route- and service-specific basis.[1] The study included a theoretical examination of the components of train resistance and investigation of locomotive efficiency with an analysis of the influence of driver behaviour. A simulation software package suitable for energy conservation was presented, as well as an analytical formulation for costing purposes. Finally, a proposed validation and development program was outlined.

A joint Transportation Development Centre/Association of American Railroads (TDC/AAR) energy program coordination meeting was held in Chicago in February 1984. At that meeting, a proposal by CIGGT to develop the model further was discussed. It was concluded that it was better for TDC and CIGGT to work on the prototype AAR Train Energy Model rather than develop another model independently. This report compares, in detail, the AAR Train Energy Model with the proposed CIGGT model. Also, the availability of existing train resistance data from the Canadian railways is addressed. Future work by CIGGT in the area of train resistance complementary to the AAR Train Energy Program is outlined.

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1 G.W. English, J.D. Young, H. Boumeester, C. Schwier, M.D. Roney and P.M. Bunting. Railway Linehaul Energy Intensity: An Analysis Leading to Design of a Train Simulation Software Package. CIGGT Report #80-15, February 1981.

2. AAR TRAIN ENERGY MODEL

Over the past few years, researchers at the AAR have developed a prototype Train Energy Model with objectives similar to those which led to the proposed model in the 1980 CIGGT study. The AAR model was evaluated at an early stage in its development and compared to the proposed CIGGT model. A working paper was written (presented in Appendix A) and discussed with the AAR development team. Other problems with input data handling, as noted in Appendix A, were of less consequence and were easily rectified.

In summary, the model uses the Davis resistance equation to simulate the movement of a train over a particular track segment on a time-step basis. The program calculates the fuel consumed and the travel time required. The fuel consumed is broken down on a throttle-notch, speed-range and resistance-component basis, as part of the model output.

Operation of the AAR Train Energy Model can be in either of two modes for all or part of the track segment under simulation. In the first mode, the computer user acts as the train engineman, specifying the various throttle or brake positions along the track segment. In the second mode, the train is under automatic or "robot" control; the model itself determines the appropriate throttle or brake position such that the train attempts to always travel at the track speed limit. The AAR researchers state that simulations made with this model have compared very favourably with actual railway field tests of fuel consumption.

A chart showing the general layout of the AAR model is shown in Figure 1. More complete descriptions of the various components of the model are presented in Appendix A.

This structure is similar to the one suggested by CIGGT. The only area of major difference was in the approach to train handling in the "robot" mode. The linear difference control used in the AAR model is considerably less complex than the one recommended by CIGGT. This approach was felt to be the source of speed "hunting" problems observed in the test run of the model. Other problems with input data handling noted in Appendix A are of less consequence and are easily rectified.

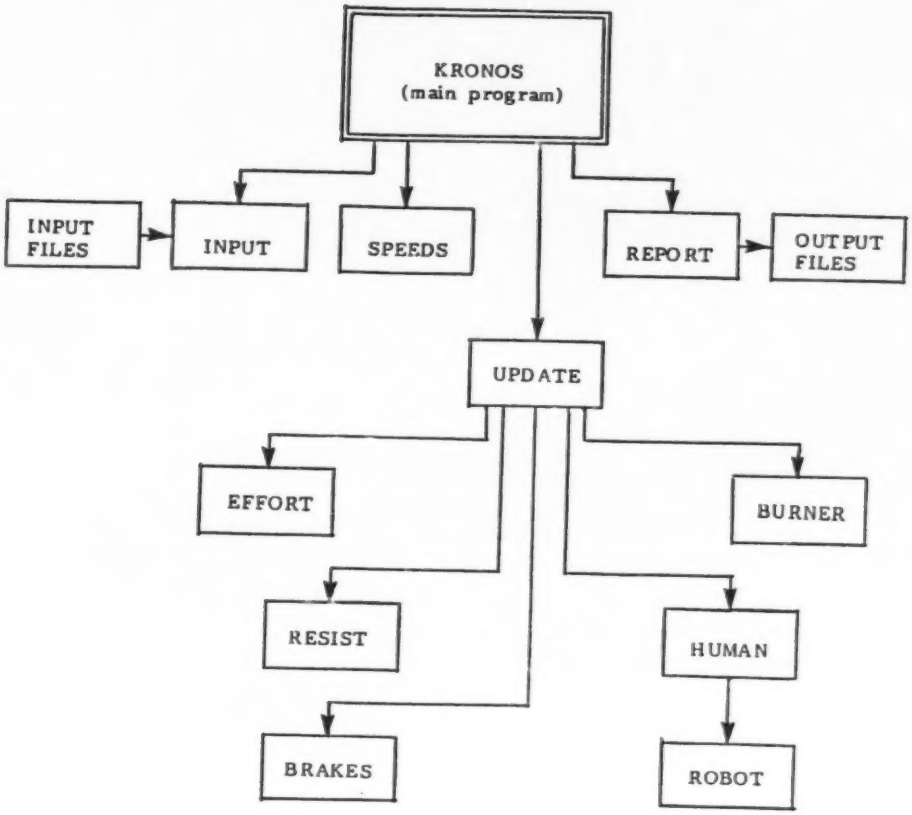

Figure 1 AAR Train Energy Model program structure

An updated version of the AAR Train Energy Model was received subsequent to our initial review. Some of the problems noted in the early version have been solved. The AAR model now carries out some of the train-specific calculations in a pre-processor. As well, a "moving-window" method of reading in the track data is now used, as opposed to the slower method of loading the entire track data file into memory at the beginning of the program run. However, the new version of the program appears to have the same speed/train control problem that was diagnosed in the original version of the program and program execution still appears to be quite slow. In addition to CIGGT, other users have been testing the program and offering feedback. Thus, the program is still in a state of evolution.

Given the modular structure, we feel that this program has the potential to become the industry standard for train energy prediction.

3. DATA AVAILABILITY

3.1 Existing Data

A review was undertaken of the availability and quality of existing data resident with CN and CP which may be relevant to train resistance. CP Rail has gathered fuel consumption data on revenue consists in various locations. However, they desire to keep these data confidential.

CN Rail has collected a number of dynamometer car recordings for revenue consists over the past decade. Many of these tests were undertaken to determine the causes of coupler failures or train action problems. However, the data collected could be quite useful in evaluating the parameters of train resistance. The data recorded include:

- a continuous reading on a five-channel strip chart recorder of throttle notch position, brake pipe pressure, speed and drawbar force
- the conductor's train journal report which indicates, for each car in the train, the identifying number, type code, contents, and gross tonnage, as well as the sequence in which they are connected (see Figure 2 for an example)
- the locomotive identification numbers
- the temporary slow orders for that train run
- the ambient temperature at departure time
- annotation of any locomotive shutdowns or unexpected train delays, and updates of train position.

These data are available for some secondary lines and some main lines, and include loaded bulk trains and mixed freight trains. For mainline runs, the track profiles are readily available in computer-readable format, while for secondary lines, condensed profile drawings are available. Other data which can be obtained include:

- hourly readings of wind speed and direction from the nearest Environment Canada weather station

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CONDUCTORS TRAIN JOURNAL REPORT

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CN 079389	E	CAB 031	41975	8	P8080	U								
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CN 857145	L	WB 079	45110	CHIPS		D					350			
CN 858028	L	WB 081	45110	CHIPS							350			
NGTXE 020780		T 028	42422	EMPTY		U					350			
CN 556074	L	B56 085	47690	LUMBER							350			
DWC 585024	L	BS1 064	47690	LUMBER							350			
CN 615067	L	F85 099	48158	LOGS		C					350			
CN 615272	L	F85 099	48158	LOGS		C					350			
GNT 004523	L	F85 100	48158	LOGS							350			
GNT 004501	L	F85 104	48158	LOGS							350			
CN 615105	L	F85 099	48158	LOGS		C					350			
GNT 004506	L	F85 104	48158	LOGS							350			

LOCOMOTIVE RECORD

Figure 2 Conductor's train journal report

- rail weight and type of joint used
- whether rail lubricators were installed.

While these data encompass many of the parameters of interest in a train resistance investigation, there is a major limitation. They are not in computer-readable format. Thus, it would be very expensive to formulate a statistically significant parametric relationship of train resistance using these data. However, they can be useful in providing point estimates under specific conditions which can be used to test the validity of preconceived parametric relationships of train resistance.

This would be particularly valuable if the data contain variability in parameters not contained in other investigations. Thus, if a statistically significant sample of a subset of the parameters involved could be obtained or if a subset of the parametric relationships were identified through laboratory investigations, the strip-chart-recorded data may be sufficient to fill in the missing relationships.

A first step would be to simply apply the various formulae for train resistance for a range of conditions to see what deviations occur in aggregate. This will be valuable in itself, as the AAR will have results available from several of their laboratory investigations of the individual components of train resistance.

Then a more methodical data reduction could be made to try to isolate as much as possible the various components of train resistance.

Table 1 illustrates the relative contribution to total train resistance of each component and the level of confidence in the causal relationship.

The objective of a detailed data analysis would be to isolate as much as possible those components which have a high magnitude and a low level of confidence in their causal relationship. A priority ranking might be:

- car dynamics
- bearing friction
- aerodynamics
- curve resistance

The effects of potential and kinetic energy changes on train resistance can be factored out of the data, since the parameters involved can be

TABLE 1

COMPARISON OF SIGNIFICANT INDEPENDENT VARIABLES AFFECTING DIFFERENT TRAIN RESISTANCE COMPONENTS

Predicted Relative Magnitude: 80-ton Car at 40 mph				
Davis	Theory	Resistance Component	Variables Included in Calculation	Confidence in Relationship
18	20	Bearing friction	Speed Journal type Journal size Ambient temperature Axle load Wheel radius	medium
27	10	Wheel/rail contact resistance	Wheel radius Wheel load Wheel profile Rail profile Yield stress of wheel steel Yield stress of rail steel	high for light axle loads
	5	Track depression resistance	Axle load Track damping Car speed Truck centre spacing Rail inertia Track modulus	low
25	45	Car dynamic resistance	Track roughness (max. allowable surface deviation) Jointed or welded Speed Gross car weight	low
30	30	Aerodynamic drag	Vehicle cross-sectional area Speed relative to wind speed Elevation Consist arrangement	medium
n/a		Curving resistance	Axle load Truck curvature Wheel diameter Wheel/rail friction coefficient Superelevation imbalance	medium
n/a		Kinetic energy losses	Journal size) Wheel diameter) car capacity	high
n/a		Potential energy losses	Train length Lengths of all gradient changes List of Δ elevations Gradient	high

obtained and the causal relationship involves accepted principles of physics. Curve resistance can be eliminated if desired, since all track segments have numerous tangent sections. Wheel/rail contact resistance may also be factored out with confidence for gross weights under 120 tons. This leaves four components: bearings, track depression, car dynamics and aerodynamics.

The uncertainty surrounding these components can be reduced under certain conditions. Aerodynamic drag can be estimated with some confidence for a uniform consist of loaded gondolas, covered hoppers or box cars under low wind conditions on the basis of extensive wind tunnel tests. Bearing resistance can be estimated with some confidence for a uniform bearing type after a long run time at one speed at summer ambient temperatures. Since track depression resistance demonstrates little speed dependency and is small in comparison with dynamic resistance, it should be possible to evaluate the accuracy of theoretical predictions of the variation of car dynamic resistance over the range of conditions encountered.

Aerodynamic resistance may be isolated on the assumption that it is the only term to be proportioned to speed raised to the second power. This assumption can be tested with more detailed data expected to be available from computer-readable data acquisition of dynamometer car runs to be made in the near future.

The dynamometer car gives an indication of drawbar pull between the locomotive consist and the trailing cars. Thus, the aerodynamic drag of the cars of a unit train consist can be estimated directly. Also, by assuming that the power output of the locomotive consist does not change significantly within the same throttle notch position over the time it takes to crest a hill, the aerodynamic drag of the locomotive consist can be estimated. This would be accomplished by comparing the net drawbar pull (i.e. tractive effort - locomotive resistance) on the upgrade at low speed to that on the downgrade at a higher speed.

In summary, the data are seen to be useful in validating models of train resistance but not in developing new statistical models. The expected level of effort required to review the data in order to isolate desired conditions and to obtain the other necessary background data is shown in Table 2.

TABLE 2

REQUIRED LEVEL OF EFFORT TO PROCESS DATA

Task	Man-days
• Obtain detail data for car, track and environmental parameters	15
• Review AAR experimental data on aerodynamics, bearings, track depression, curving and car dynamics	15
• Develop dynamometer car data review objectives and methodology	5
• Develop computer models of the various formulae of train resistance	8
• Undertake the data search for the desired isolation conditions	15
• Compare data with predictions	5
• Reiterate for further independent checks of some data where desired	5
• Use any confirmed relationships to further isolate other components	10
• Draw appropriate conclusions from the data analysis	5
• Report on findings and procedure	10
Total	93

3.2 Imminent Data

In the course of discussions with both railways about train resistance data, it was learned that additional resistance tests with revenue trains were planned for 1985. CN Rail Operations invited CIGGT to participate in their tests.

CP Rail also invited CIGGT to participate in tests they are planning for the Thompson subdivision. The two sets of data will be extremely complementary. The CN tests will be on high-speed track (95 mph passenger limits) with very little curvature. The test consists will be TOFC express trains with uniform car types. The CP tests will be on high-curvature track with much lower speed limits. The test consists will be unit coal trains, loaded and empty. It is anticipated that the range of axle loads, track surface error, curvature, speed and aerodynamic shape will be sufficient to use as a base for statistical evaluation of all parameters of train resistance. As the CP test procedure involves the digitization of data in the field, no additional instrumentation is required.

3.2.1 Test Proposal in Conjunction with CN Rail's Intermodal Tests

CN Rail will be carrying out comparative train resistance tests on old and new intermodal cars between Toronto and Montreal in August 1985. Eight test runs will be made -- three runs with older piggyback cars and five runs with new "5-pack" style cars. These test runs will alternate between Toronto and Montreal. The test consist will consist of two GP40-2 locomotives, a CN dynamometer car (#15100), 55 intermodal cars, and a caboose.

We propose to place two propeller-generator anemometers on a boom attached to the front of the leading locomotive. These anemometers record wind speed and direction acting on the locomotive. A $1/12^{th}$ scale model of the locomotive would be placed in the National Research Council's (NRC) Low Speed Wind Tunnel in order to examine the effect of the locomotive's front shape on the anemometer calibration.

The dynamometer car is equipped with a strain-gauged draft gear assembly which measures draw bar buff and draft. A pressure transducer will be installed in the locomotive air-brake reservoir in order to

determine locomotive independent brake pressure. The dynamometer car is equipped to measure train-line brake pressure and its own cylinder pressure. From a 27-pin, multiple unit cable attached to the locomotives, the dynamometer car measures throttle position. The dynamometer car also records train speed, gradient and milepost (through an event marker).

As the on-board instrumentation is limited to a multi-pen strip-chart recorder, we propose to install a Honeywell Model 101 Data Tape Recorder on the car in order to record the following parameters:

- anemometer voltages
- train speed
- draw bar pull
- gradient
- milepost
- brake pipe pressure
- locomotive independent brake pressure
- test car brake cylinder pressure

A subcontract to NRC's Railway Lab would be initiated for installation and calibration of the onboard instrumentation.

Prior to the start of testing, the line will be examined in order to determine level or constant grade sections suitable for acceleration and coast-down testing. For each direction, three or four sections will be selected. A sample of one of the proposed test sections is shown in Figure 3. If schedule time permits, accelerations from a variety of starting spaces will be carried out over the sections, as well as non-powered, non-braking, coast-down tests.

Before each run, the length and gap spacing of each piggyback trailer on the train will be measured using a sonic distance measuring device. Each piggyback trailer will be weighed as well. This will be combined with the empty car weight in order to calculate the total train weight. In order to measure the fuel consumed, the locomotives will be refuelled from a metered fuel truck after each run.

To permit analysis of energy dissipation in the suspension system, measurements of the track condition will be made. This will be accomplish using data obtained from CN's track geometry car (#15000). The geometry measures crosslevel, left rail surface, right rail surface,

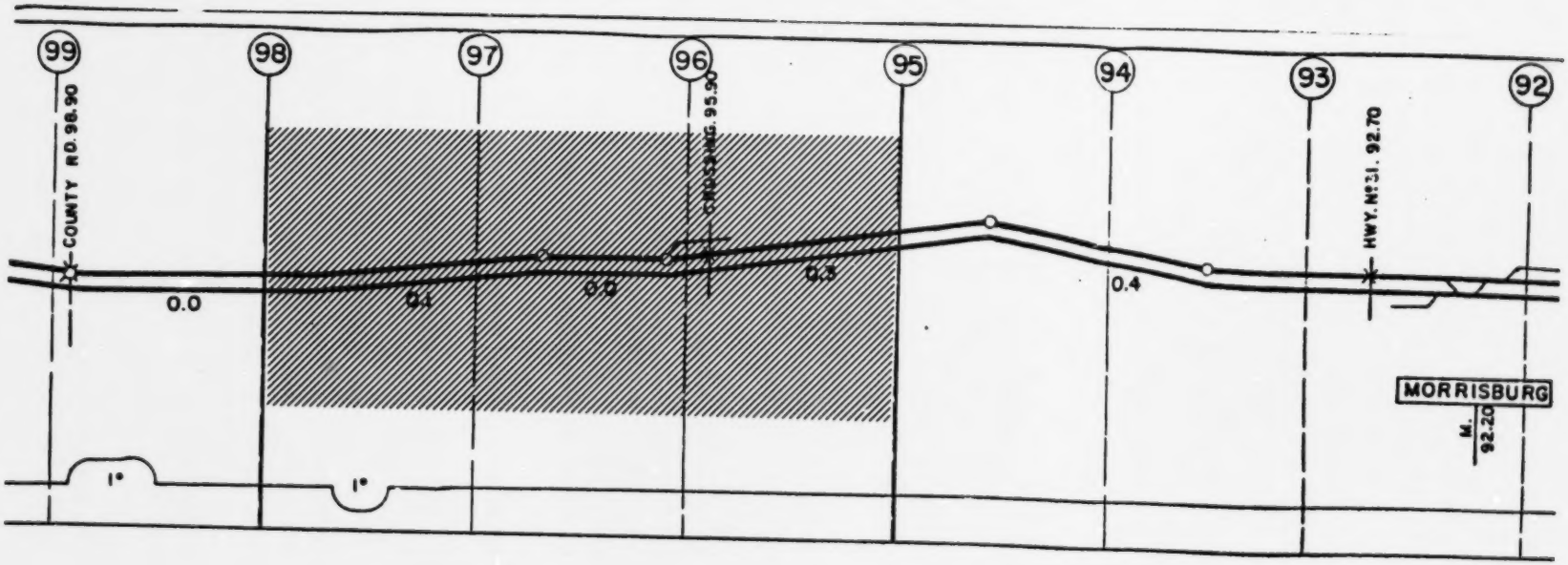

Figure 3 A sample proposed resistance test section

curvature, gauge and superelevation. The Honeywell 101 tape recorder will be placed on board to record these parameters over the track section.

The analog tape recordings made on both the geometry and dynamometer cars will be digitized using a personal computer. This will permit easier evaluation of the data.

The next stage in the proposed work will be the interpretation, reduction, and analysis of these data. The first step will be one of data validation -- checking the recorded information against manual or separate observations. For example, existing track profile data will be compared with on-board inclinometer and track geometry car data. As well, the aerodynamic data must be interpreted, the propeller speeds converted to a vector representation of air speed, and the wind tunnel calibration coefficient applied. The resulting air speed indication will be used along with measured train speed to check the implicit wind speed and direction with weather reports for the same location and time.

The data reduction step will involve a number of parameters. The effects of potential and kinetic energy changes on train resistance will be factored out of the data. The track geometry car data will be passed through a Fourier transformation to obtain power spectral densities (PSD) for surface, cross-level and alignment variations by track segment (three to five miles). In addition, the dynamometer car data will be segmented by other characteristics such as degree of curvature, train speed, yaw angle of the air speed, concrete versus wood tie sections, and track quality as indicated by PSDs.

While numerous forms of data reduction will be undertaken in association with the statistical evaluation outlined below, the original data will be retained for possible future investigations where the nature of the data is relevant.

The next step will be the analysis of the data. This will take two forms: regression analysis and hypothesis testing. The regression analysis will begin with a derivation of the coefficients for the Davis formula. It will then add parameters such as air speed, yaw angle and

track PSDs, and try other speed exponents to see if an improved fit can be obtained.

The hypothesis tests will focus on obtaining a statistically significant validation of some of the theoretical or laboratory relationships of the parameters of train resistance. Various theoretical and laboratory-based causal relationships now exist and the Train Resistance Committee of the AAR is planning to have additional tests of bearing resistance, track depression resistance and aerodynamic drag for TOFC consists in place through the latter half of 1985.

The priority of a detailed data analysis would be to isolate, as much as possible, those components which have a high magnitude and a low level of confidence in their causal relationship.

- car dynamics
- bearing friction
- aerodynamics
- curve resistance

The effects of potential and kinetic energy changes on train resistance can be factored out of the data, since the parameters involved can be obtained and the causal relationship involves accepted principles of physics. Curve resistance can be eliminated if desired, since all track segments have numerous tangent sections. Wheel/rail contact resistance may also be factored out with confidence for gross weights under 120 tons. This leaves four components: bearings, track depression, car dynamics and aerodynamics.

Bearing resistance can be estimated with some confidence for a uniform bearing type after a long run time at one speed at summer ambient temperatures. Track depression resistance demonstrates little speed dependency and is small in comparison with dynamic resistance, and aerodynamic effects can be factored out by searching for track quality changes with the same train speed. Thus, it should be possible to evaluate the accuracy of theoretical predictions of the variation of car dynamic resistance over the range of conditions encountered.

Aerodynamic drag may be evaluated on the assumption that it is the only term to be proportioned to speed raised to the second power. This assumption can be tested in the regression analysis. The dynamo-

meter car gives an indication of drawbar pull between the locomotive consist and the trailing cars. Thus, the aerodynamic drag of the cars of the TOFC or COFC consists can be estimated directly. Also, by assuming that the power output of the locomotive consist does not change significantly within the same throttle notch position over the time it takes to crest a hill, the aerodynamic drag of the locomotive consist can be estimated. This would be accomplished by comparing the net drawbar pull (i.e. tractive effort - locomotive resistance) on the upgrade at low speed to that on the downgrade at a higher speed.

APPENDIX A

REVIEW OF THE AAR TRAIN ENERGY MODEL

A.1 INTRODUCTION A.1
A.1.1 Overview of Prototype AAR Train Energy Model A.1

A.2 DETAILED DESCRIPTION OF THE AAR PROTOTYPE TRAIN ENERGY MODEL A.3
A.2.1 Main Program KRONOS A.3
A.2.2 Subroutine INPUT A.4
A.2.3 Subroutine SPEEDS A.6
A.2.4 Subroutine UPDATE A.6
A.2.5 Subroutine RESIST A.7
A.2.6 Subroutine BURNER A.7
A.2.7 Subroutine EFFORT A.7
A.2.8 Subroutine OUTPUT A.8
A.2.9 Subroutine HUMAN A.9
A.2.10 Subroutine ROBOT A.9
A.2.11 Subroutine BRAKES A.9
A.2.12 Subroutine REPORT A.9

A.3 COMPARISON WITH SUGGESTED CIGGT TRAIN ENERGY CONSUMPTION CALCULATOR A.3
A.3.1 Overview of CIGGT Model Design A.3
A.3.2 Main Program A.3
A.3.3 Resistance Preprocessor A.5
A.3.4 Locomotive Preprocessor A.5
A.3.5 Train-Handling Preprocessor A.6
A.3.6 Main Stepping Algorithm A.6
A.3.7 Duty Cycle Stepping Algorithm A.7

A.4 POTENTIAL AREAS FOR MODEL ENHANCEMENT A.8
A.4.1 Train Control A.8
A.4.2 Stepping Algorithm A.17
A.4.3 Data Handling A.17

A.1 INTRODUCTION

As part of a 1980 study for Transport Canada to examine the feasibility of developing a computer program to estimate railway linehaul energy use, CIGGT put forth a system software design for a train energy consumption calculator. In the past few years, researchers at the Association of American Railroads in the United States have been developing a prototype Train Energy Model. The CIGGT model approach was intended to be a research tool. The objective of the AAR model development was more applications oriented. This relaxes the need for detail in some areas, but the overall structure would be expected to be quite similar. The AAR researchers indicated their desire to follow many of the recommendations in the 1980 study and asked CIGGT to review their computer program at an early stage of development for conformity. The program is under continuous evaluation and has been evaluated at an early stage of development. The objective of this working paper is to evaluate, in detail, the AAR Train Energy Model structure and compare it to the structure recommended by CIGGT. Based on this analysis, recommendations for future model development work will be made.

A.1.1 Overview of Prototype AAR Train Energy Model

The model uses the Davis resistance equation to simulate the movement of a train over a particular track segment on a time-step basis. The program calculates the fuel consumed and the travel time required. The fuel consumed is broken down on a throttle-notch, speed-range and resistance-component basis, as part of the model output.

Operation of the AAR Train Energy Model can be in either of two modes for all or part of the track segment under simulation. In the first mode, the computer user acts as the train engineman, specifying the various throttle or brake positions along the track segment. In the second mode, the train is under automatic or "robot" control; the model itself determines the appropriate throttle or brake position such that the train attempts to always travel at the track speed limit. The AAR researchers state that simulations made with this model have compared very favourably with actual railway field tests of fuel consumption.

A chart showing the general layout of the AAR model is shown in Figure A.1. More complete descriptions of the various components of the model follow.

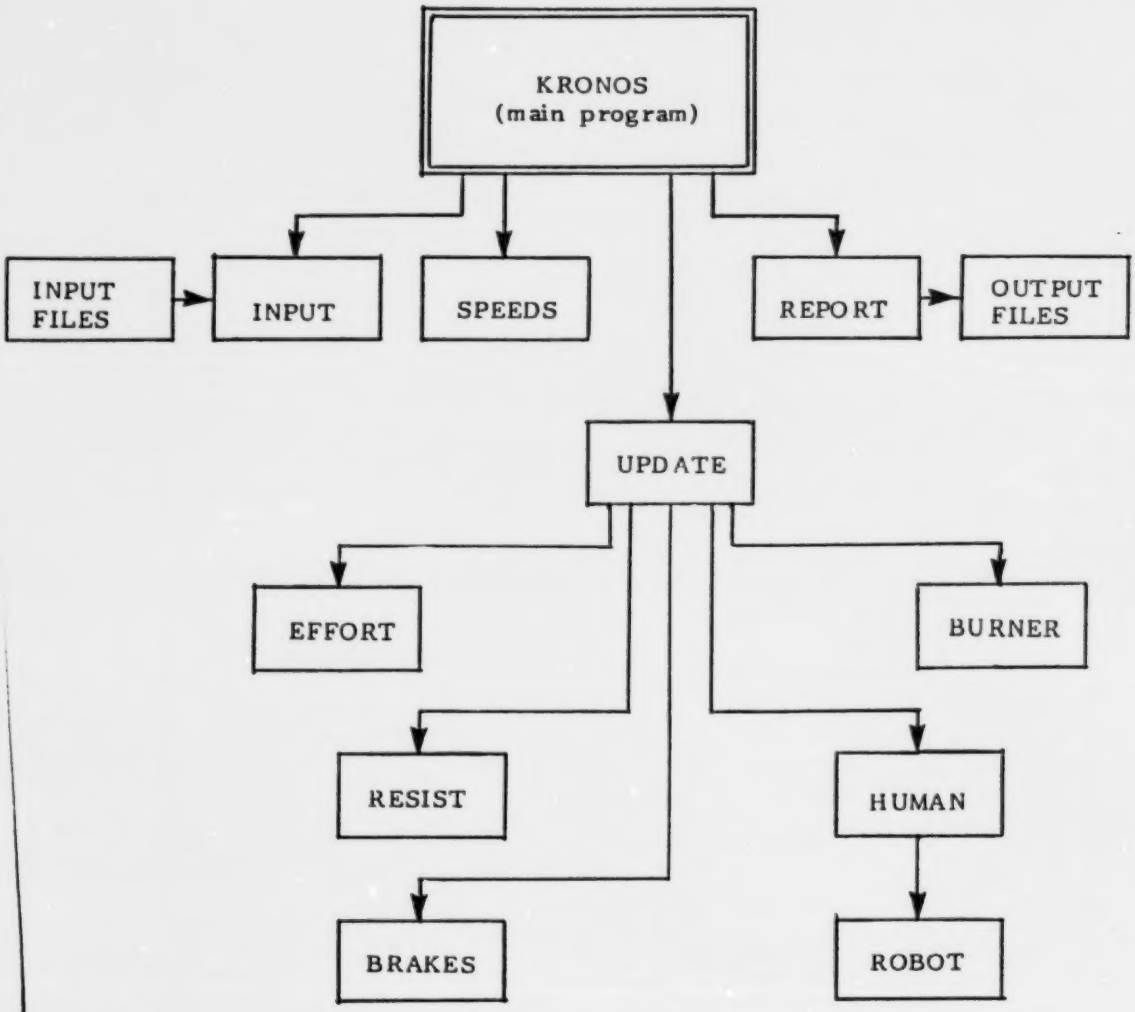

Figure A.1 AAR Train Energy Model program structure

A.2 DETAILED DESCRIPTION OF THE AAR PROTOTYPE TRAIN ENERGY MODEL

A.2.1 Main Program KRONOS

The main program itself does very few calculations: it calls the various routines that perform the simulation and documents the results. The program begins by initializing the following variables:

- coefficient of grade resistance
- time increment
- gravitational constant
- total fuel consumed
- total work done

Through computer input/output, the program requires the user to input the initial position of the train, the final position of the train (destination), the "look-ahead" distance, and the reference speed (if different from the speed limits given in the track data files). The program then requires the user to input the desired type of Davis resistance equation coefficients, eit er "Davis," "CN" or "Other." If "Other" is chosen, the necessary coefficients must be entered on the screen by the user at this point. The user is then queried by the program as to:

- the type of curve resistance simulation (either "contant" or "variable")
- the presence of lubrication on curved and tangent track
- the per cent reduction in train resistance due to lubrication on tangent track.

The main program now calls subroutine INPUT to assemble the required data from stored disk files for the simulation. Then, subroutine SPEEDS is summoned to calculate the equilibrium speeds for each of the throttle notch settings. Subroutine UPDATE is called to perform the actual simulation of the train movement over the track segment. The program then calls subroutine REPORT to create the output files. The main program then terminates.

A.2.2 Subroutine INPUT

This subprogram reads in the track and train data files and assembles them for the simulation. Based on the name of the track data file given by the user, the routine opens the appropriate file and the following values are read in (for each track data point):

- distance from initial position in feet
- elevation of track
- per cent grade
- degree of curvature
- track speed limit
- milepost number (to nearest tenth of a mile)
- place name (if any)

(As a note, a track data point occurs if elevation, curvature or track speed limit change.) The routine next computes the average curvatures and average positive gradient for the track segment. The user is then asked to input the train consist file name on the screen. Based on the name given, the correct file is opened and the data items are read in, including:

- number of locomotives in the consist
- type of each locomotive and its dynamic brake type
- number of cars in the consist
- each car type and weight of lading.

The routine then calculates the total number of vehicles in the consist, as well as the total train lading. For each locomotive in the consist, the locomotive characteristics are obtained from the applicable locomotive data file. The parameters read in are:

- number of axles on locomotive
- dead weight of locomotive
- weight due to inertia of rotating parts
- length of locomotive
- ten fuel consumption rates (for the eight throttle positions as well as "idle" and "dynamic braking mode")

Based on the total weight of the locomotives, the adhesion-limited maximum tractive effort is calculated. (The program assumes a maximum limit of 23 per cent.) The routine next reads in the characteristics of each car in the consist from the appropriate data file, including:

- number of axles on car
- empty weight of car
- gross rail load of car
- length of car
- aerodynamic drag coefficient
- truck type (regular steerable)

The aerodynamic coefficients of the locomotive are assigned, then the routine calculates the total aerodynamic coefficient of the train, the total weight and total length of the train, as well as the total gross rail load. The locomotive independent air brake force per unit pressure reduction is computed next. From the air brake data file the following parameters are obtained:

- maximum brake pipe pressure
- brake application delay time
- brake release delay time.

The subroutine now proceeds to calculate a table of air brake force per unit pressure change values for brake application (at one second increments from one to one hundred and twenty seconds). Similarly, a table of air brake force per unit pressure change values for brake release is also computed (on the same time basis). Using a reference deceleration rate based on a 26 psi brake pipe pressure reduction, it calculates the point along the track section at which the brakes must be applied to ensure the train stops at the end of the track segment.

The constant component of resistance for the entire train is next calculated by the routine. The tractive effort and dynamic braking tables for each specific locomotive are read in from the corresponding data files. The tractive effort and dynamic braking effort tables are summed for all locomotives in the consist. The fuel consumption rates for each value in the aggregated tractive effort and dynamic braking effort tables are determined.

The speed limit at each point is altered to the speed limit at the "look ahead" distance. Finally, the subroutine reads in the curve resistance table for various degrees of curvature, truck types and curve conditions.

A.2.3 Subroutine SPEEDS

This routine calculates the equilibrium speeds (at which tractive effort equals total train resistance) for each of the eight throttle notch positions. The total train resistance is calculated from the train resistance, grade resistance (based on the average positive gradient for the track segment), and the curve resistance (based on the average curvature for the track segment). It outputs the values to the screen for the information of the user.

A.2.4 Subroutine UPDATE

Subroutine UPDATE is the main stepping algorithm of the train energy model. The subroutine first initializes the position of the train on the track segment such that the rear of the train is at the initial track position. Output files to record the simulation and operator-set throttle and brake positions are opened. The stepping algorithm begins at this point. Subroutine RESISTANCE is called to calculate the train resistance at the beginning of the time interval. Subroutine BURNER is then called on to compute the fuel consumption. In order to record the simulation, the routine next calls subroutine OUTPUT to write out the current values of various parameters to output files. Subroutine HUMAN is then summoned in order to obtain the user-specified throttle or brake settings. If the model is under automatic control (i.e. the program itself chooses the correct settings in order to keep the train at the speed limit), subroutine ROBOT is in turn called on to calculate the settings. If the train is braking, subroutine BRAKES is called in order to determine the brake force. The routine then calls subroutine EFFORT to calculate the tractive effort of the locomotives, as well as the power output. From the tractive effort and the train resistance, the locomotive drawbar force and the acceleration rate at the beginning of the interval is calculated. The time increment to the end of the interval is computed based on the acceleration rate. The time is then advanced to the end of the interval. Using a Taylor series expansion,

the distance travelled by the train during the time interval is calculated. A first estimation of the velocity at the end of the time interval is made. Using this velocity estimate, the resistance and tractive effort of the train at the end of the time interval are calculated by calling subroutines RESIST and EFFORT, respectively. The routine now calculates the work done by resistance and the air brakes as well as the power at the end of the interval. The incremental work done by the diesels is then calculated. The end of the interval acceleration is computed. Using the average of the acceleration at the beginning and end of the time interval, the velocity at the end of the interval is re-estimated. The kinetic energy, total work, total work error, fuel/work and fuel/distance ratios are calculated. The routine now loops back to the beginning of the stepping algorithm to model the next time step.

A.2.5 Subroutine RESIST

Subroutine RESIST calculates the total train resistance using the Davis equation. The grade and curve resistance components are calculated on a per-car basis based on the position along the track of the centre of gravity of each car. The grade and curve resistances are then summed for all the cars in the train.

A.2.6 Subroutine BURNER

This subroutine calculates the amount of fuel consumed by the locomotives during the time interval. The fuel consumed is determined by the throttle position and is summed for all the locomotives in the consist.

A.2.7 Subroutine EFFORT

Depending on the mode of operation (throttle or braking), this subroutine calculates either total tractive effort or the total dynamic braking force. Both the tractive effort and the dynamic braking force are obtained through a table look-up, depending on the throttle or braking position and train speed. In the case of the locomotive throttle, there are eight discrete notch positions. For dynamic braking, eight braking positions are used, even though in reality the

dynamic brake can be applied at various settings due to rheostat control. Apparently, this method of modelling was chosen because braking effort data supplied by locomotive manufacturers use eight "dynamic braking positions" due to the complex nature of the dynamic brake systems.

A.2.8 Subroutine OUTPUT

Subroutine OUTPUT writes a number of quantities to a disk file for each interval of the simulation. The quantities are listed below:

- elapsed time
- acceleration rate
- velocity
- current speed limit
- milepost number
- per cent grade
- curvature
- train position
- track elevation
- operational mode (ROBOT or MANUAL control)
- throttle notch position
- dynamic brake position
- work done
- drawbar force
- horsepower output of locomotives
- brake pipe pressure
- brake force
- fuel/work ratio
- time-averaged fuel/work ratio
- fuel/distance ratio
- time-averaged fuel/distance ratio
- speed limit efficiency.

As well, under manual control the subroutine outputs the following values to the screen for the information of the user:

- elasped time
- position
- "look ahead" speed limit
- milepost number
- per cent grade
- curvature
- place name (if any).

A.2.9 Subroutine HUMAN

This subroutine permits the user to act as engineman for the train by manually inputting the throttle or brake position. If the train is under automatic control, the subroutine in turn calls subroutine ROBOT to determine the throttle or brake settings.

A.2.10 Subroutine ROBOT

Subroutine ROBOT determines the throttle or brake setting needed to maintain the train at the speed limit. The routine also stops the train at the destination, at the constant reference deceleration rate.

A.2.11 Subroutine BRAKES

This routine computes the air brake force as a function of time for both the locomotive independent air brake and the train air brake. The air brake force is based on the initial brake pipe pressure, the amount of brake application (i.e. the reduction in brake pipe pressure), and the time since brake application.

A.2.12 Subroutine REPORT

Subroutine REPORT sums the energy consumption distributions by resistance component, speed range and throttle position, and outputs them to a disk file. The routine also provides the time spent in each speed range and throttle position.

A.3 COMPARISON WITH SUGGESTED CIGGT TRAIN ENERGY CONSUMPTION CALCULATOR

A.3.1 Overview of CIGGT Model Design

In CIGGT Report #80-15, entitled Railway Linehaul Energy Intensity: An Analysis Leading to Design of a Train Simulation Software Package, the system design of the CIGGT Train Energy Model was presented. The criteria for the model included two major requirements. First, the recommended model would be designed to operate as a train energy simulator which would be responsive to various train handling techniques. Second, the model would be able to utilize a fixed duty cycle in order to permit sensitivity analyses to be carried out on track and vehicle characteristics. Because the model would be used as a research tool, it was suggested that a modular design be adopted. This would allow for easy modifications and the inclusion of new material rather quickly. The resulting schematic flowchart for the program is shown in Figure A.2. The recommended model is composed of six major segments:

- the main program, which basically provides the interface between the user and the various system modules
- three preprocessors: resistance, locomotive and train handling to process the master data files
- a main stepping algorithm
- a duty cycle stepping algorithm to perform the actual simulation.

The "heart" of the CIGGT model is the main stepping algorithm. It simulates the movement of a train over a specified track segment. It consists of:

- a train-handling module, which modifies the locomotive control settings as it moves through the track segments
- a locomotive module, which calculates the tractive effort and power required during each step of simulation

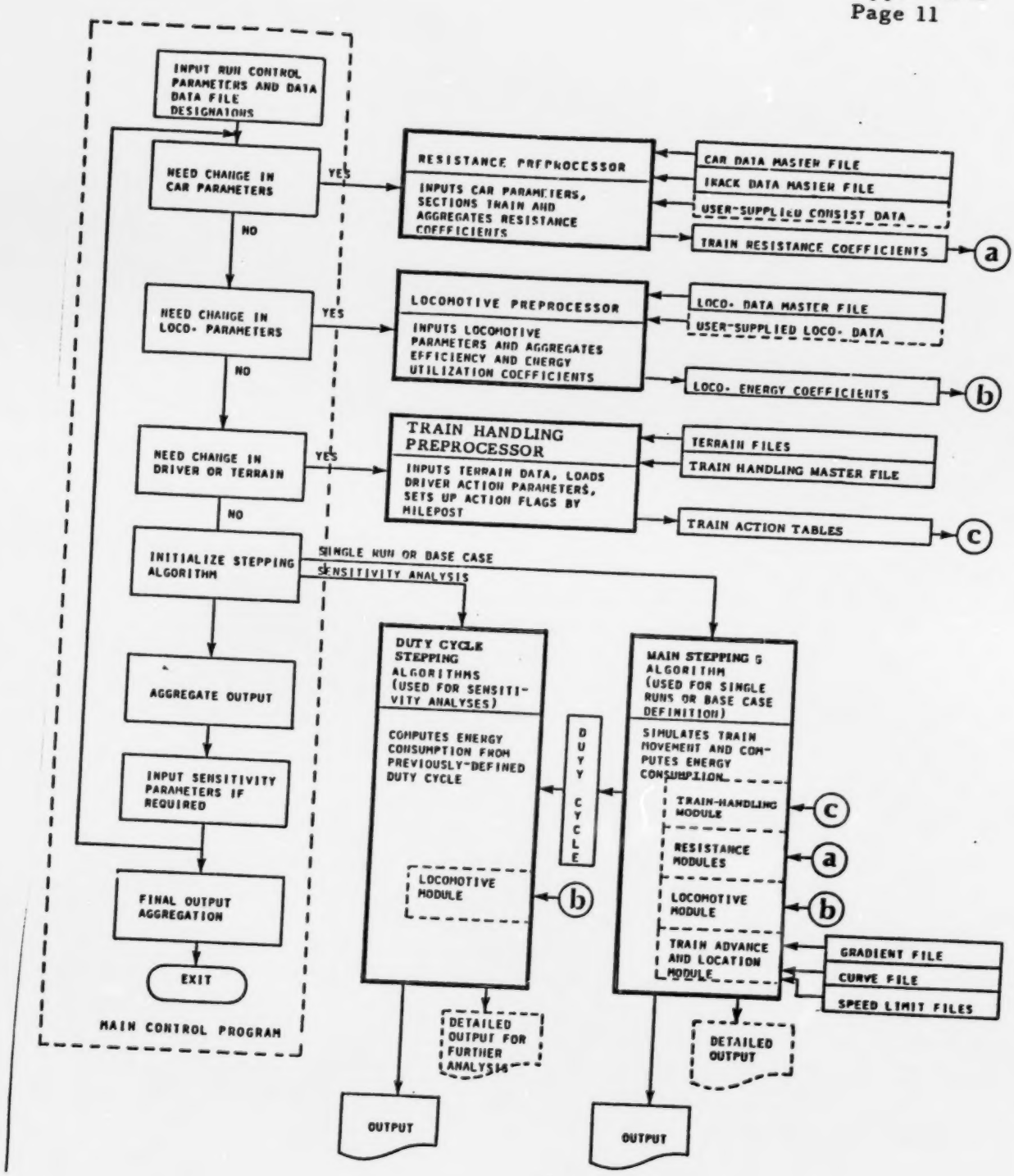

Figure A.2 CIGGT Train Energy Consumption Calculator

- a resistance module, which calculates the total train resistance based on the location, speed, acceleration and brake condition of the train

- a train advance module which moves the train to the next point and calculates the time elapsed.

In the following section the AAR Train Energy Model will be compared to the structure for the recommended CIGGT model.

A.3.2 Main Program

KRONOS, the main program of the prototye AAR Train Energy Model, is quite similar in design to the criteria prescribed in the CIGGT system. It is a relatively simple program, controlling several subroutines to provide the reduction of input data, the actual simulation, and aggregation of the output. As per the CIGGT suggested design, key parameters are entered in the main program. The only major omission from KRONOS is the provision to perform repetitive "sensitivity analysis" runs using essentially unchanged track, train and train handing data for each run. To carry out this form of analysis currently, separate runs must be made within the AAR model with all parameters being recalculated each time, somewhat reducing the model's efficiency as a research tool.

A.3.3 Resistance Preprocessor

As defined in the CIGGT model, the resistance preprocessor aggregates (on a car-by-car basis) those components which do not vary with location along the track. In the AAR prototype model, the resistance coefficients are read in (or assigned) in subroutine INPUT. As well, the coefficients are summed to determine the overall components of resistance of the train within the routine. A table of curve resistances by degree of curvature, truck type and curve condition is read in. More detailed models of aerodynamic and track depression resistance (similar to those outlined in the CIGGT model design) could be incorporated in the preprocessor.

A.3.4 Locomotive Preprocessor

The purpose of the locomotive prepocessor in the CIGGT model is to aggregate the tractive effort, dynamic braking effort and fuel consumption data for use in the main simulation algorithm. In the AAR prototype train energy model, these necessary calculations are carried out in subroutine INPUT. It should be noted that the tractive effort and dynamic braking data are entered in table form in the AAR model. This existing structure does not accommodate different locomotive minimum speeds and adhesion for the "worst case."

A.3.5 Train-Handling Preprocessor

The train-handling preprocessor, as defined in the CIGGT model, determines the action required (i.e. application of throttle or brake) based on the terrain and train-handling techniques selected. The AAR program does not incorporate this level of detail in its train-handling simulation; hence, there is no equivalent model to the train-handling preprocessor.

A.3.6 Main Stepping Algorithm

The main stepping algorithm used in the AAR model is quite similar to that of the proposed CIGGT model. In the AAR model it is contained in subroutine UPDATE.

The major difference is due to the fact that the CIGGT model would operate on a distance-based algorithm, whereas the AAR model operates on a time-based algorithm. Subroutine EFFORT performs the tractive effort calculations as outlined in the CIGGT locomotive module. Similarly, subroutine RESIST is the equivalent of the planned resistance module.

The train-handling module in the CIGGT program would modify the locomotive control settings to either reduce, increase or maintain train speed, depending on the actions determined in the train-handling preprocessor. The AAR model deals with the area of train control somewhat differently. As mentioned previously, the user has two options regarding control of the train: the various control settings can be

entered directly through subroutine HUMAN, or they can be calculated by the program in subroutine ROBOT. The AAR prototype model calculates the control settings (either throttle or brake) on the basis of the train's speed at a given point relative to the speed limit value.

The train advance module of the CIGGT model advances the train along the track to the next inflection point as part of each iteration in the main stepping algorithm. Changes in track gradient, curvature, or speed limit constitute an inflection point. As well, inflection points can occur if the train-handling preprocessor identifies certain handling actions for specific terrain conditions. There would be preset limits to the minimum step size to keep the program running time to a reasonable limit and overriding constraints on the maximum speed change in a step.

The train-advancing calculation is carried out in the prototype AAR Train Energy Model as part of the subroutine UPDATE. During each iteration of the AAR model stepping algorithm, the size of the time step is determined from the acceleration/deceleration rate. The larger the acceleration/deceleration rate, the smaller the time step size. The model currently limits the step size from one to thirty seconds. Test run comparisons with an existing TPC showed the AAR model to be much slower, although this was partly due to problems in the train handling algorithm of the AAR program.

A.3.7 Duty Cycle Stepping Algorithm

In the CIGGT model, the duty cycle stepping algorithm is used for sensitivity analyses in energy consumption. The energy calculations are made based on a predetermined duty cycle. The duty cycle could be determined from the main stepping algorithm.

A.4 POTENTIAL AREAS FOR MODEL ENHANCEMENT

As a result of the comparative analysis of the prototype AAR Train Energy Model to the proposed CIGGT Train Energy Consumption Calculator, areas of potential model enhancement have been identified. These topics will be addressed in the following sections.

A.4.1 Train Control

As mentioned previously, the AAR model calculates eight equilibrium speeds. These are the points at which tractive effort (for each of the eight throttle notch settings) equal total train resistance. The program utilizes the average positive gradient of the track section in question to calculate the grade resistance. These equilibrium speeds are used by the automatic train control routine to select the throttle notch positions in order to maintain the train at the track speed limit. The method has some shortcomings when applied to track segments with certain track features. As an example, the model was used to simulate the movement of a loaded unit train on CP Rail's main line from Stephen, B.C. to Golden, B.C. This track segment is nearly all steep descending (negative) gradients. Since the resistance calculations were based on the average positive gradient (which was essentially non-existent), the equilibrium speeds were not truly characteristic of the track segment. Under the control strategy of continual throttle and braking to keep the train at the speed limit, problems occurred. The actual train speed fluctuated widely, with several occurrences of substantial over-speeding. Figure A.3 illustrates the train speed plotted against the speed limit for the track segment. A more elaborate train-handling model would improve the simulation's response to specific track cases. A train-handling routine, as outlined in the description of the CIGGT model, which provides various train control options based on terrain conditions would be a possible model refinement.

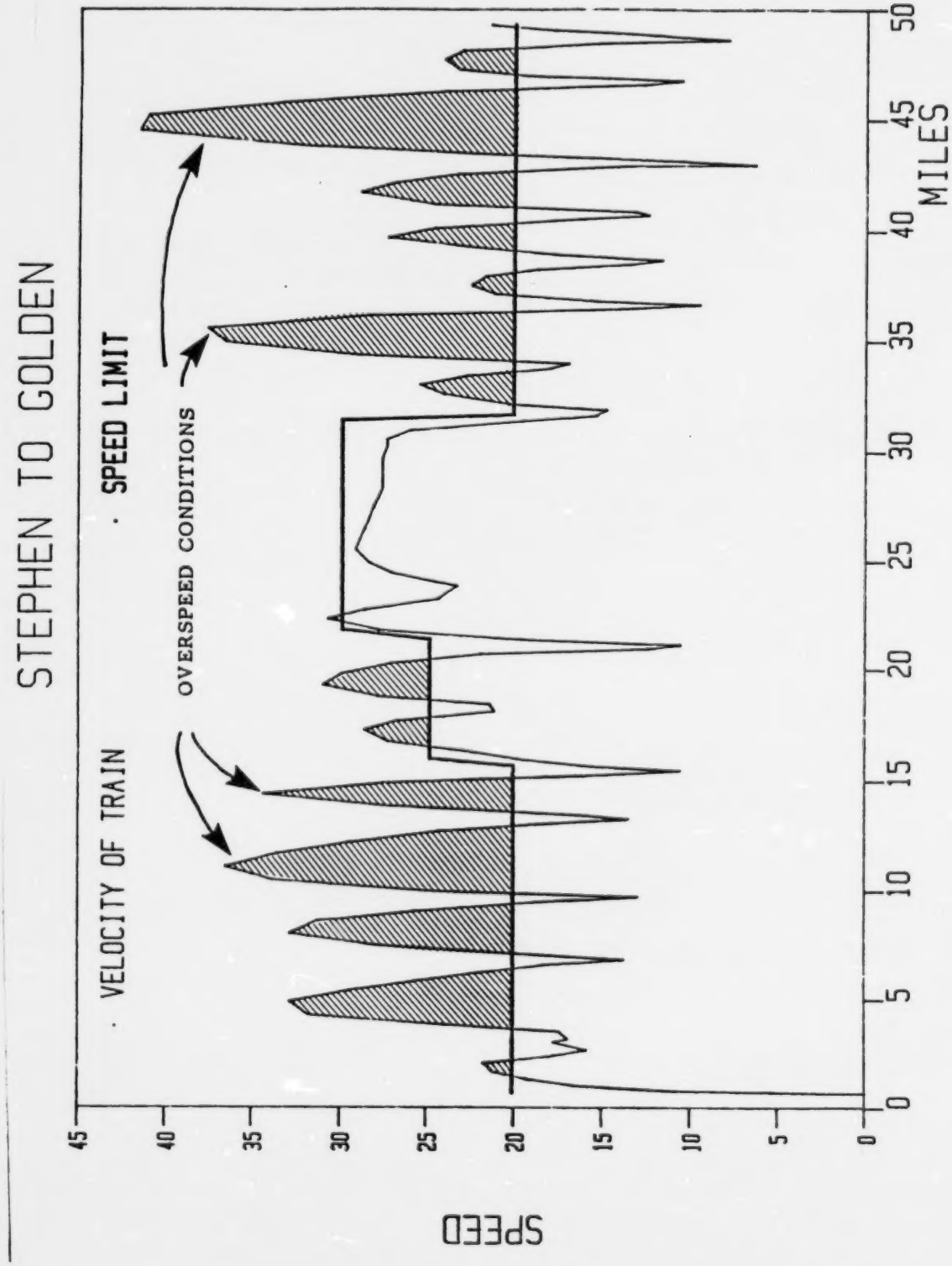

Figure A.3 Speed versus distance

A.4.2 Stepping Algorithm

As discussed earlier in the report, the AAR model uses a time-based stepping algorithm, with the size of the time step inversely proportional to the acceleration/deceleration rate of the train. With the train continually applying throttle and brake (accelerating and decelerating) to maintain train speed at the speed limit, the step size is kept to the minimum value -- one second. Often, at slow speeds this results in the train moving less than one car length during an iteration step. Distance increments such as this require an exceedingly long time to simulate train movement through long track sections. For example, the model requires over two hours of computational time on an IBM XT Personal Computer to simulate train movement over a fifty-mile-long track segment.

A distance-based stepping algorithm moving the simulation from one change in track characteristic to another (inflection point to inflection point) would require substantially less simulation steps, with a large gain in the program operational efficiency.

A.4.3 Data Handling

Currently, the AAR model track data file is arranged such that a data item containing distance from initial position, elevation of track, per cent grade, degree of curvature, track speed limit and milepost number is required each time elevation, track speed limit or curvature varies. This results in a sizeable number of redundant data points being stored in the program arrays, which, in turn, limits the size of the track segment that can be used in the program.

An alternative to this would be separate files for the changes in curvature, speed limit and elevation. As well as reducing the size of the required data files, it would allow compatibility with track data that has already been obtained from the Canadian railways.

Another refinement in data handling would be the development of "true" preprocessors to assemble the train characteristics, so that repetitive runs of the model would not require the recalculation of the aggregate resistance coefficients, total train length, weight, etc. From the examination of the program, it was noticed that a sizeable number of

data items were "hard-coded" within the program logic. Placement of these data items in proper data files would permit greater user flexibility.

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